A Process-Oriented, Landscape-Scale Approach to Soil and Vegetation Restoration in a Degraded Sahelian Agroecosystem

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1. Abstract

Throughout the Sahel of Africa, grain crops grown in the valleys are intermingled with the shrublands of the plateaus. In Hamdallaye, Niger, heavy grazing and fuelwood harvest have fragmented the banded shrubland mosaic that is typical of the plateau vegetation cover in this region. The soil structure that enabled high infiltration rates under the shrub cover degraded to crusted soils with very low infiltration rates after the vegetation cover was removed. This degraded the hydrologic function of the plateau shrublands to the point of generating extensive runoff that resulted in severe downslope flooding and erosion which disrupted agronomic activity in the valleys. A restoration approach was adopted to reestablish the banded shrublands on the plateau and thereby reestablish hydrologic function of the agroecosystem landscape. A network of microcatchments was established in a pattern that reconnected the remaining fragments of shrub cover. These microcatchments harvested runoff, suspended nutrients, and sediment thereby creating an environment conducive to vegetation reestablishment. Planted seedlings of native shrubs grew very slowly but planted seedlings of *Acacia holosericea* (a hardy, rapid growing, nitrogen fixing, exotic species that had been introduced to Niger in the 1950's) was able to thrive within the microcatchments. Within three years, the *A. holosericea* had grown to 3 m height and created a favorable microenvironment promoting the autogenic succession of native herbaceous and shrub species. Hydrologic function of the plateau improved to the point of reducing flooding and erosion hazard downslope. Eleven years after the establishment of *A. holosericea*, most soil chemical characteristics represented by pH, total carbon, and exchangeable bases had recovered to similar levels as those found in native shrub bands. Available P remains significantly lower than in the native shrublands soils, likely due to the P uptake traits of *A. holosericea*. Infiltration rate and microbial activity have recovered to the level of native shrub bands.

2. Introduction

A landscape characterized by lateritic plateaus bisected by valleys with deep sandy soil occurs throughout the Sahel. Throughout this region an agroecosystem mosaic of grain crops (primarily millet, sorghum, and cowpeas) grown in the valleys is intermingled with the rangelands of the plateaus (Manu et al. 2000). The historic rangeland plateau vegetation is characterized by alternating bands of shrubs and bare ground corridors aligned parallel to the contour of gentle slopes (<2%). This striped vegetation pattern, frequently referred to as “tiger bush”, is commonly found on shallow silt or clay textured soils with gentle slopes in arid and semi-arid landscapes of the world (Valentin & d’Herbès 1999). The genesis of the striped vegetation pattern has been the subject of considerable research and is summarized in special issues devoted to this subject in Catena (Volume 37(1-2) 1999) and Acta Oecologica (Volume 20(3) 1999). The functional effect of this pattern is that runoff from the crusted soils is redistributed to the vegetation bands which have much higher infiltration rates, forming a natural water harvesting system.

Heavy communal use of the rangelands for fuelwood harvest and grazing leads to fragmentation of the shrub bands, disrupting the ability of the shrub bands to harvest runoff, thereby contributing to collapse of the banded shrub mosaic (Wu et al. 2000) and seasonal flooding problems for downslope farming activity (Manu et al. 2000). The impetus for this study was generated by local communities seeking to stop flooding and gully formation originating on the degraded rangelands. Extensive dam structures to capture and retain runoff from the degraded rangeland were not economically feasible. Therefore, the objective of this study was to determine if hydrologic function of the degraded portions of the fragmented shrub bands could be re-established through the implementation of soil and vegetation reclamation techniques.

3. Methods

The research was conducted near Hamdallaye, Niger (13°34'N, 2°35'E), a rural community approximately 35 km north-east of Niamey. The long-term average annual rainfall at the study site was 480 mm, with most rain occurring as high intensity storms from June through September. The highest average monthly maximum temperature of 41^{o}C occurs in April and the lowest average monthly minimum temperature of 17^{o}C occurs in January. The soil of both the tiger bush fragments and the intervening crusted corridors were classified as a Typic Psammentic Kandiustalf.

Previous observations by Institut National de Recherches Agronomiques du Niger scientists had established that degraded rangelands were not able to be rehabilitated simply by excluding livestock and fuelwood harvest. Furthermore, they had determined that there was 100% mortality of tree seedlings when they were planted into the crusted soils. Various microcatchment configurations were tested to harvest runoff and thereby aid seedling establishment. Tests of the survival and growth rates of native tree species composing the tiger bush indicated that native tree seedlings planted in the microcatchments were able to survive, but they grew very slowly, thereby limiting their ability to rapidly ameliorate the soil and hydrologic characteristics of the site. However, an Australian species (*Acacia holosericea*) was found to thrive when planted in microcatchments (Manu et al. 2000). Therefore, the treatment for the study was chosen to be 1 m diameter U-shaped microcatchments located on barren soils in a manner that would reconnect the tiger bush fragments. The microcatchments were spaced at 1 m intervals so that the group of microcatchments was 11 m wide (six rows of microcatchments). The length of these treatment sites was determined by the distance between tiger bush fragments and ranged between 25 m to 50 m. Twelve replications of microcatchments blocks were created, with each block (treatment replication) containing between 75 and 150 microcatchments. The microcatchments within 8 of the blocks were planted with one *A. holosericea* seedling per microcatchment. The microcatchments within 4 of the blocks were left unplanted, to test whether microcatchments alone were able to jump-start a succession sequence. Measurements collected within these treatment blocks were compared with measurements that were collected within 4 tiger bush fragments. By agreement with the local community, livestock use of the area was limited from 1991 to 1996 to light, infrequent grazing. No fuelwood harvest was allowed. After 1996 the use pattern was left to the discretion of the community who chose to allow harvest of dead wood for fuel but did not allow cutting of live branches or trees. Heavy livestock stocking rates resumed in 1996.

Surface soils samples (0-5 cm) were collected in November of 1991, 1995 and 2003 to evaluate the long-term impact of reforestation activities. The 1991 samples were not replicated. The 1995 and 2003 samples were collected in both the microcatchment trench and in the area midway between microcatchments. Soil pH was determined in a 1:1 soil:water ratio. Phosphorus (P) was extracted with Bray-1 P solution and the P in solution determined colorimetrically. Total carbon (C) was determined by dry combustion using LECO Truspee. Ammonium acetate (pH 7) was used to extract calcium (Ca), magnesium (Mg) and potassium (K). Base concentrations were determined using atomic absorption spectroscopy. The number and activity of the soil microbial reactions and activity were determined by running a GN microplate as an ecoplate using a Biolog MicroStation System methodology.

A double-ring infiltrometer was used to estimate relative treatment differences in infiltration rate; the diameter of the inner ring was 30 cm and the diameter of the outer ring was 50 cm. Water was added and maintained at a constant depth of 10 cm, with the amount of water added to the ring recorded in 5 minute increments for 30 minutes, a period of time sufficient for reaching a steady-state terminal infiltration rate.

Analysis of variance was conducted to determine if treatment differences within a sample date existed. If differences were present the Newman-Keuls test was used to separate the means between treatments at $P<0.05$.

4. Results and Discussion

Sediment began to accumulate within the microcatchments in conjunction with the runoff events that soon followed their completion. *A. holosericea* seedlings planted into these microcatchments had a 96% survival rate and exhibited rapid growth (30 cm tall at planting in 1991, 390 cm tall in 1995, 454 cm tall in 2003). Accumulation of litter biomass and maintenance of extensive ground cover (Table 1) was apparently facilitated by the slow decomposition rate associated with the high lignin and phenol content of the *A. holosericea* leaves. The rapid deposition of both water and wind-borne sediment in all microcatchments, and the accumulation of litter in the microcatchments planted with *A. holosericea,* was accompanied by recovery of microbial enzymatic activity in the soil and an observed notable increase in macroinvertibrate activity (especially termites) that converted crusted soil to a very friable nature when under litter cover. This was accompanied by an enhancement of infiltration rate to levels comparable with the native tiger bush (Table 1).

Available bases were significantly lower in the soils of the barren corridor than the tiger bush sites (Table 2). The Ca concentrations in the microcatchment treatments showed a general increasing trend, but by 2003 the Ca concentrations were generally still not significantly different than the barren corridor soils. In contrast, Mg concentrations were similar to the tiger bush soils by 1995 and tended to be greater than the concentrations in the tiger bush soils by 2003. Potassium concentrations tended to be higher in the microcatchment treatments than in the tiger bush soils in 1995 but dropped to similar levels as the tiger bush soils by 2003. Iron and aluminum oxides present in the soil were exposed during construction of the microcatchments, probably leading to increased K availability as the soil weathered, followed by a decline as K was taken up by plants or leached from the soil.

Table 1 Ground cover, litter biomass, median enzyme reactions and infiltration rates 41 months (November, 1995) and 137 months (November, 2003) after the microcatchments were constructed and planted with *A. holosericea* seedlings in July, 1992. Means within the same column with the same letter are not significantly different (P<0.05)

Treatment	Ground Cover (%)		Litter Biomass (kg ha^{-1})	Median Enzyme Reactions	Infiltration Rate (mm hr^{-1})
	1995	2003	1995	1995	1994
Tiger Bush (TB)	83b	76b	3,230c	37a	40.6a
Microcatchment with Acacia					
Microcatchment	100a	100a	30.880a	30a	31.3a
Microcatchment Interspace	61bc	86b	4,880b	11b	14.1b
Unplanted Microcatchment					
Microcatchment	56c	23d	560d	31a	30.6a
Microcatchment Interspace	1e	Trace f	40e	5b	3.8 c
Barren Corridor	Trace e	Trace f	20e	2b	1.6c

Trees can act as 'cation pumpers' obtaining Ca and Mg from deep in the soil and transporting them up to the leaves which eventually are deposited on the soil surface as litter. Deposition of base cations also occurred due to the accumulation of wind blown sediments. Aeolien sediments captured at the study site were found to provide 8 kg ha^{-1} yr^{-1} Mg, 6 kg ha^{-1} yr^{-1} Ca, 3 kg ha^{-1} yr^{-1} K and 1 kg ha^{-1} yr^{-1} Na (Drees et al 1993).

Table 2 Base cation (Ca, Mg, K) soil concentrations in the top 5 cm of soil 8 months (November, 1991) before the microcatchments were constructed and 41 months (November, 1995) and 137 months (November, 2003) after the microcatchments were constructed and planted with *A. holosericea* seedlings in July, 1992. Means within the same column with the same letter are not significantly different (P<0.05)

Treatment	Ca (cmol(+) kg^{-1})			Mg (cmol(+) kg^{-1})			K (cmol(+) kg^{-1})		
	1991	1995	2003	1991	1995	2003	1991	1995	2003
Tiger Bush (TB)	1.54	1.95a	2.27a	0.65	0.60ab	0.42bc	0.25	0.26b	0.22b
Gap bewteen TB fragments	1.29			0.52			0.12		
Microcatchment with Acacia									
Microcatchment		1.06cd	1.20bc		0.56ab	0.68ab		0.35ab	0.28ab
Microcatchment Interspace		1.30bc	0.99c		0.44bc	0.63ab		0.32ab	0.31a
Unplanted Microcatchment									
Microcatchment		1.42b	1.53b		0.53ab	0.69ab		0.40a	0.18bc
Microcatchment Interspace		0.61d	1.15bc		0.79a	0.72a		0.32ab	0.19bc
Barren Corridor	0.87	0.99cd	0.71c	0.41	0.36c	0.26c	0.19	0.16c	0.12c

Soil pH within the microcatchments was similar to the tiger bush by 1995, while the barren corridor and microcatchment interspaces maintained a significantly lower pH (Table 3). By 2003 the interspace between the microcatchments planted with *A. holosericea*, which had an increase of litter ground cover to 86%, had a pH similar to the tiger bush. Cations released as the litter decomposed and sediment accumulated were likely responsible for this amelioration of pH. The relationship between soil pH and enzyme reaction data in the soil was anticipatable since bacteria and actinomycetes are more active near neutral pH.

Extractable P in the treatments associated with *A. holosericea* plantations had become significantly lower than the other treatment categories by 2003. Uptake of extractable P by *A. holosericea* and storage in the root system is a likely explanation since P appears to be a highly mobile element with *A. holosericea* as shown by Langkeam and Dalling (1982) who documented that 85% of the phyllode total P was remobilized into the tree before phyllode fall, a rate that is higher than most other acacia species.

Total C in the microcatchments increased over time, with the *A. holosericea* microcatchments being statistically similar to the tiger bush by 2003. The total C in the interspace between the *A. holosericea* microcatchments began to increase by 2003 as the leaf litter from the trees increased, while the total C in unplanted interspace and barren corridor soils did not change. The high lignin and phenol content of the *A. holosericea* leaves likely contributed to the relatively slow recovery of total C. Photo-decomposition and respiration from bacterial activity within the litter layer may also have resulted in a significant loss of C from the leaf litter to the atmosphere.

Table 3 Soil pH, extractable P and total C in the top 5 cm of soil 8 months (November, 1991) before the microcatchments were constructed and 41 months (November, 1995) and 137 months (November, 2003) after the microcatchments were constructed and planted with *A. holoserecia* seedlings in July, 1992. Means within the same column with the same letter are not significantly different (P<0.05)

	pH			Extractable P (mg kg^{-1})			Total C (mg kg^{-1})		
Treatment	**1991**	**1995**	**2003**	**1991**	**1995**	**2003**	**1991**	**1995**	**2003**
Tiger Bush (TB)	5.2	5.4a	5.3a	8.55	7.53a	7.13b	0.65	0.65a	0.67a
Gap Between TB Fragments	5.1			7.26			0.24		
Microcatchment with Acacia									
Microcatchment		5.2a	5.3a		7.83a	5.48c		0.39b	0.65a
Microcatchment Interspace		4.9b	5.2a		8.03a	5.89c		0.27c	0.45b
Unplanted Microcatchment									
Microcatchment		5.4a	5.1ab		6.64b	8.59a		0.43b	0.38b
Microcatchment Interspace		4.7b	4.8b		8.98a	8.26a		0.20c	0.26c
Barren Corridor	4.9	4.8b	4.8b	7.39	7.99a	8.34ab	0.24	0.24c	0.26c

5. Management Implications

Farmers in the region of Hamdallaye, Niger recognized that flooding and gully formation threatening their livelihood escalated in conjunction with the degradation of the upland rangeland vegetation community. To restore hydrologic function within the watershed it was necessary to reclaim the degraded rangeland systems, but simply removing the source of disturbance (fuelwood harvest and heavy grazing) had been tried throughout the region and was observed to be unsuccessful. Therefore, microcatchments were established to help hold water and nutrients on the crusted landscape with the hope of jump-starting an autogenic succession sequence that would reestablish the rangeland vegetation community and associated hydrologic function. Microcatchments planted with the hardy, fast-growing *A. holosericea* successfully created conditions that reestablished soil and infiltration properties and reduced downslope flooding. This practical reclamation procedure has been independently adopted by other local communities who marshal their own resources to construct the microcatchments, plant the seedlings, and change rangeland use patterns. *A. holosericea* typically has a 10 to 20 year life span and a very low reproduction potential in this environment. Therefore, the next step of the research at the Hamdallaye site was to plant the slower growing native tree species in the understory of the *A. holosericea*. In sum, this reclamation process followed a two step process, the first using fast growing hardy introduced species planted in microcatchments to quickly re-establish hydrologic function and soil nutrients, followed by the second step of planting the native tree species in the understory with the intent of eventually repopulating the shrub bands with the native tree species.

6. References

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